Probing nuclear short-range correlations in two-nucleon knockout reactions

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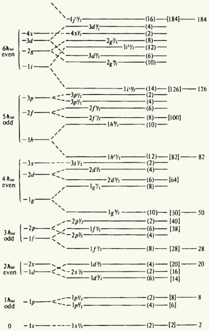
Nuclei in all their facets: IPM, SRC, LRC

Independent Particle Model (IPM)

- Solve 1b Schrodinger equation in a **mean-field** potential
- Nucleons have an identity: $\alpha_i(n_i, l_i, j_i, m_i, t_i)$ and $\psi_{\alpha_i}(\vec{r})$
- Average quantities: $\langle T_p \rangle, \langle U_{pot} \rangle, \langle \rho \rangle, \ldots$



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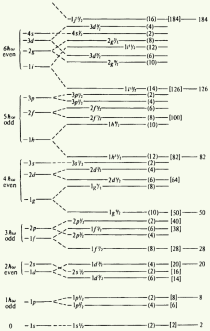


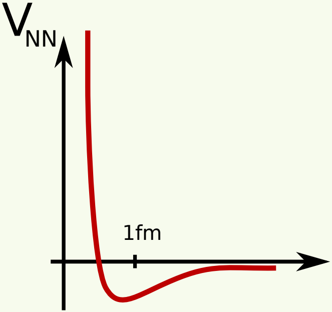
Long Range Correlations (LRC)

- Nucleons loose their identity
- Spatio-temporal fluctuations: $\Delta T_p, \Delta U_{pot}, \Delta\rho, \ldots$
- "Most" nucleons get involved ($\sim R_A$)
- Energy scale $\Delta E \approx$10 MeV
- Exp. observed, th. understood [giant resonances in $\gamma^{(*)}(A, X)$]

Short Range Correlations (SRC)

- Nucleons loose their identity
- Spatio-temporal fluctuations: $\Delta T_p, \Delta U_{pot}, \Delta\rho, \ldots$
- "Few" nucleons get involved ($\sim R_N$)
- Energy scale $\Delta E \approx$100 MeV
- Exp. observed, th. understood [2N knockout in $A(e, e'X)$]

Nuclear short-range correlations (SRC)



Warning: reductive picture!!

- *NN*-force: intermediate-range attraction, short-range repulsion ("hard core")
- Induce high-momentum tails in momentum distributions
- Universal across the nuclear mass range (**local** character of SRC)
- Correlated nuclear wave funtion Ψ: act with **correlator operators** $\hat{\mathcal{G}}$ (short-range structure) on Φ (mean-field quantum numbers + long-range structure)

$$|\Psi\rangle = \hat{\mathcal{G}}|\Phi\rangle$$

- Useful proxy: large majority of SRC stems from IPM *NN* pairs in a $n = 0, \ell = 0$ **relative *S*-state**
  M. Vanhalst et al., PRC86, 044619 ('12)

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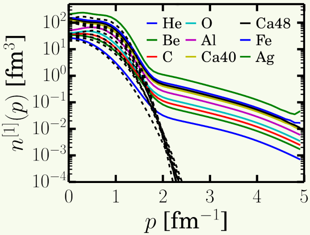

J. Ryckebusch et al.,JPG42 055104 ('15)

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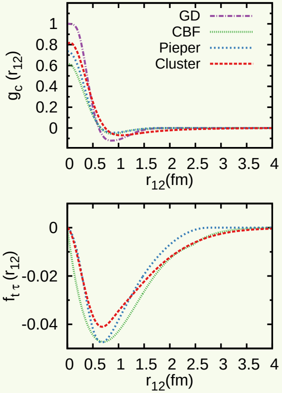

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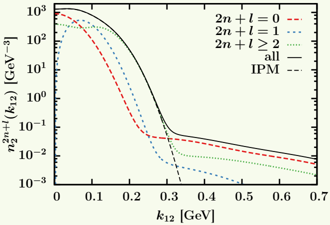

^{56}Fe relative momentum distribution

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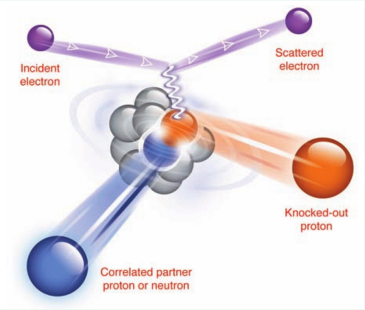
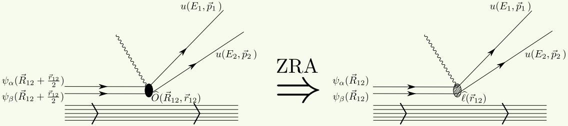
Probing SRC

Electroinduced two-nucleon knockout $A(e, e'NN)$



- Triple coincidence measurement (hard)
- Energy transfer, Momentum transfer : $\omega = E_e - E_{e'} \qquad \vec{q} = \vec{k}_e - \vec{k}_{e'}$
- Four momentum transfer : $Q^2 = \vec{q} \cdot \vec{q} - \omega^2$ *The higher Q^2 the smaller the distance scale probed!*
- Bjorken scaling variable : $x_B = \frac{Q^2}{2m\omega}$
  - $1 < x_B \leq 2$: single nucleon contribution $k < k_F$ dies off, sensitive to **high initial momenta** associated with $2N$ configurations

Exclusive $A(e, e'NN)$ reactions



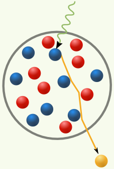
For close proximity pairs $\vec{r}_{12} \approx 0$ (Zero-Range Approximation, ZRA) the $(e, e'NN)$ cross section factorizes as,

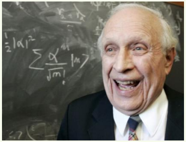
$$\frac{\mathrm{d}^8\sigma(e, e'NN)}{\mathrm{d}^2\Omega_{k_{e'}}\mathrm{d}^3\vec{P}_{12}\mathrm{d}^3\vec{k}_{12}} = K_{eNN}\,\sigma_{e2N}(\vec{k}_{12})F^D(\vec{P}_{12})$$

- $\sigma_{e2N}(\vec{k}_{12})$ encodes the electron coupling to a correlated nucleon pair
- $F^D(\vec{P}_{12})$ is the two body center of mass momentum distribution of SRC pairs (= probability to find correlated pair with c.m. momentum $\vec{P}_{12}$)
- $F^D(\vec{P}_{12})$ is normalized to number of short-range correlated pairs in nucleus, contains effect of **final-state interactions** of outgoing nucleons

J. Ryckebusch, PLB383 1-8 ('96)
C.Colle et al., PRC89 024603 ('14)

Hadron-nucleon FSI with Glauber scattering theory





- Glauber theory has origins in optics
- High-energy diffractive scattering: small angles
- Applicable when wavelength of scattering particle is significantly smaller than interaction range $\rightarrow$ momenta of a few 100 MeV
- Eikonal method: outgoing wave gets complex phase $\phi_{\text{scat}}(r) = e^{i\chi(r)}\phi_{\text{in}}(r)$

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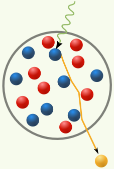

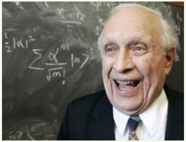

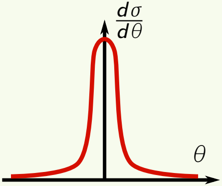

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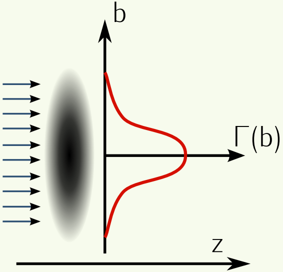

- Grey disc scattering: introduce Gaussian profile function

$$\phi_{\text{scat}}(r) = (1 - \Gamma(b))\,\phi_{\text{in}}(r)$$

- Profile function can be related to the hN scattering amplitude through a FT
- Parametrised with three energy-dependent parameters

$$\Gamma_{\text{hN}}(\vec{b}) = \frac{\sigma^{\text{tot}}_{\text{hN}}(1 - \mathrm{i}\epsilon_{\text{hN}})}{4h\beta^2_{\text{hN}}} \exp\left(-\frac{\vec{b}^2}{2\beta^2_{\text{hN}}}\right)$$

- Multiple scattering: phase-shift additivity $e^{i\chi_{\text{tot}}} = \prod_i \left(1 - \Gamma_i(\vec{b}_i)\right)$ (frozen approximation)

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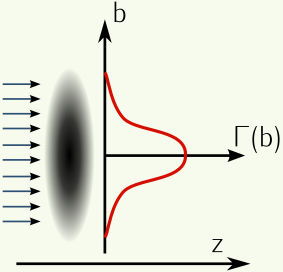

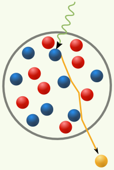

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Mass dependence of pN SRC

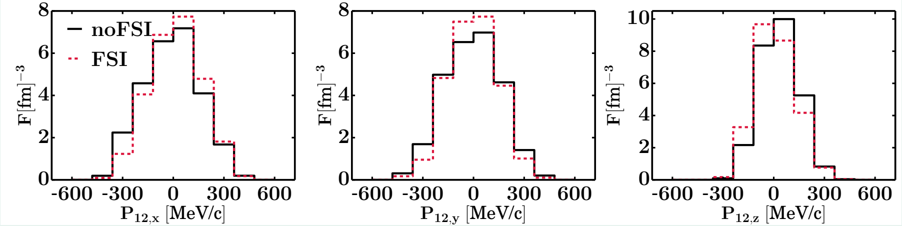
- Mass dependence of SRC-pairs investigated in exclusive $(e, e'pN)$ reactions can be investigated through cross section ratio

$$\frac{\sigma[A(e,e'pN)]}{\sigma[^{12}C(e,e'pN)]} \approx \frac{\int \mathrm{d}^2\Omega_{k_{e'}} \mathrm{d}^3\vec{k}_{12} K_{\mathrm{epN}} \sigma_{\mathrm{epN}}(\vec{k}_{12}) \int \mathrm{d}^3\vec{P}_{12} F_{\mathrm{A}}^{D}(\vec{P}_{12})}{\int \mathrm{d}^2\Omega_{k_{e'}} \mathrm{d}^3\vec{k}_{12} K_{\mathrm{epN}} \sigma_{\mathrm{epN}}(\vec{k}_{12}) \int \mathrm{d}^3\vec{P}_{12} F_{^{12}\mathrm{C}}^{D}(\vec{P}_{12})}$$

$$\approx \frac{\int \mathrm{d}^3\vec{P}_{12} F_{\mathrm{A}}^{D}(\vec{P}_{12})}{\int \mathrm{d}^3\vec{P}_{12} F_{^{12}\mathrm{C}}^{D}(\vec{P}_{12})}$$

- Experimentally also preferred as a lot of systematic errors and corrections drop out when taking the ratio

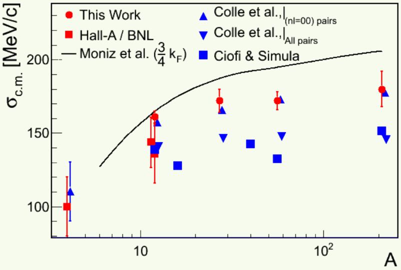
Center of mass momentum distribution



- The c.m. momentum distribution for $^{12}C(e,e'pp)$ of ZRA **close proximity** correlated proton pairs (width $\sim$ 154MeV). The width of the c.m. momentum distribution of all pairs differs significantly ($\sim$ 140MeV).
- The inclusion of final-state interactions has limited effect on the shape of the c.m. momentum distribution apart from a significant attenuation. (The dashed FSI line has been multiplied with a factor of 4 here!)

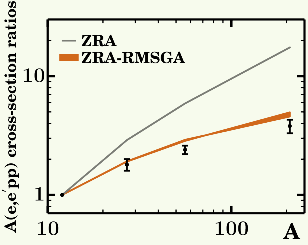
C.m. motion of correlated pp pairs

DATA IS PRELIMINARY! (COURTESY OF O. HEN AND E. PIASETZKY)



- Analysis of exclusive $A(e, e'pp)$ for ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb by Data Mining Collaboration at Jefferson Lab
- Distribution of events against P_{cm} is fairly Gaussian
- $\sigma_{c.m.}$: Gaussian widths from a fit to measured c.m. distributions
- Clearly in good agreement with theory calculations for correlated pairs

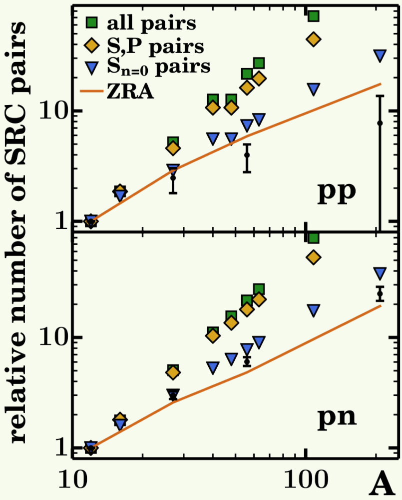
Mass dependence of pp cross section ratio



C.Colle et al. PRC92 024604 ('15)

- $\frac{\sigma[A(e,e'pN)]}{\sigma[^{12}C(e,e'pN)]} \approx \frac{\int \mathrm{d}^3\vec{P}_{12} F^D_{\mathrm{A}}(\vec{P}_{12})}{\int \mathrm{d}^3\vec{P}_{12} F^D_{12_{\mathrm{C}}}(\vec{P}_{12})}$
- Data from data mining initiative for the Jefferson Lab CLAS collaboration (4π detector, **huge phase space**)
- Calculations performed for ^{12}C,^{27}Al,^{56}Fe and ^{208}Pb.
- Number of correlated pairs scale softer than $Z(Z-1)$
- Final-state interactions soften the mass dependence further
- Charge-exchange effects in final-state interactions also taken into account

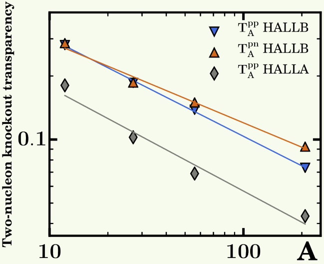
Mass dependence of SRC pairs



arXiv:1503.06050, C. Colle et al.

- Instead of correcting "probed" SRC pairs for FSI and CE interactions we can correct data → estimation of number of SRC pairs.
- Extracted data compared with the results from the zero-range approximation and several counting schemes (only $n = 0$, $\ell = 0$ relative S-pairs, S&P-pairs, all pairs)
- Again good agreement with data and calculations only including SRC-susceptible pairs

Mass dependence of transparencies in $A(e, e'pN)$



C. Colle et al., in preparation

- Transparency is defined as the ratio of a cross section including final-state interactions to one without. As such it provides a measure for the attenuation of the nuclear medium.
- For single-nucleon knockout one has a robust mass dependence $T_p \propto A^{-0.3}$
- Here we compare two calculations for double nucleon knockout: one with a almost 4π phase space (HALLB), one with a very limited one (HALLA)
- Absolute values differ, but both obey a robust power law $T_{pp} \propto A^{-0.45}$

Summary

- The number of SRC pairs can be estimated by counting the close proximity pairs in a nucleus (relative distance ≈ 0).For close proximity pairs the $A(e, e'pN)$ cross section factorizes into
  - relative momentum part containing the photon-2 nucleon coupling
  - c.m. momentum part containing the probability distribution of the SRC nucleon pairs.
- The mass dependence of the number of SRC prone pairs is much softer than a naive combinatorial prediction ($Z(Z-1)$ for pp and NZ for pn). Inclusions of final state interactions have a large effect on the mass dependence and soften it substantially.
- Calculations are in agreement with Jefferson Lab CLAS data.
- Transparency of the $A(e, e'pp)$ reaction can be captured in a robust power law $T \propto A^{-\gamma}$ with $0.4 \leq \gamma \leq 0.5$